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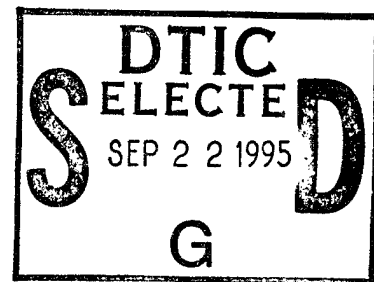
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PATENT APPLICATION

REACTIVE OXYGEN-ASSISTED ION IMPLANTATION INTO METALS AND  
PRODUCTS MADE THEREFROM

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Background of the Invention

1. Field of the Invention

The present invention relates in general to implanting ions into a substrate metal and more particularly to improving the corrosion resistance of a substrate metal by implanting ions therein using oxygen in the ion implantation vacuum chamber.

2. Description of the Related Art

In general, the corrosion resistance of various metals such as iron-based alloys, aluminum, and aluminum-based alloys is provided by an oxide film which forms on the surface of the normally active metal and which prevents degradation by the environment. However, in environments that contain anions, such as chloride, the oxide film is locally degraded causing a loss of passivity and localized corrosion.

In the case of aluminum and aluminum alloys, it has been proposed to introduce alloying elements which improve corrosion resistance. However, such alloying elements create intermetallic phases which can disrupt the oxide film. Also, the alloying elements which improve corrosion resistance may be inconsistent

Docket No.: N.C. 76,497  
Inventor's Name: Sartwell et al.

PATENT APPLICATION

1 with strength considerations. Moreover, most alloying elements  
2 which improve corrosion resistance have a limited solubility in  
3 aluminum.

4 It has also been proposed to form a solid solution surface  
5 alloy with surface modification techniques. Such surface  
6 modification techniques are non-equilibrium techniques, introducing  
7 alloying elements to a concentration beyond the normal solubility  
8 limits. The surface modification techniques, such as ion  
9 implantation, use a directed energy beam. More specifically it has  
10 been proposed to implant chromium ions into iron and low-alloy  
11 steel thereby producing a surface layer similar to stainless steel.  
12 Also, implantation of tantalum ions into low alloy steel was found  
13 to produce a surface which was somewhat more corrosion resistant  
14 than that for chromium implanted low alloy steel. For aluminum and  
15 aluminum alloys, it has been proposed to introduce molybdenum or  
16 tantalum atoms to increase the resistance to pitting.

17 One of the factors which limits the effectiveness of surface  
18 modification using ion implantation is sputtering, the erosion of  
19 atoms as a result of the impact of the incident ions being  
20 implanted. In the initial portion of the ion implantation process,  
21 atoms of the substrate metal are sputtered away. However, as the  
22 implantation progresses, the concentration of the implanted species  
23 increases and the erosion starts to effect the implanted species.  
24 Eventually the loss of atoms from sputtering equals the rate of  
25 implantation. At this point a steady state is reached. The steady

1 state concentration can be given by  $100\%/(S + 1)$ , where S is the  
2 sputter coefficient expressed in atoms removed per incident atom  
3 (atoms/ion).

4 It has been found that when tantalum atoms are implanted into  
5 steel at an implantation energy of 150 keV, the sputter coefficient  
6 is approximately 9. Therefore, the resulting surface concentration  
7 based on the formula  $100\%/(S + 1)$  is 10 atomic %. The maximum  
8 concentration of tantalum is at the surface of the substrate metal  
9 (steel in this case), and the peak tantalum concentration is  
10 greater than 5 atomic % and the implanted region extends to a depth  
11 of only 250 Å (1 microinch). While the tantalum-implanted steel  
12 exhibits some improvement in corrosion resistance, the low surface  
13 concentration is believed to limit such improvement in corrosion  
14 resistance.

15 As an alternative to using ion implantation, it has been  
16 proposed to deposit a coating on the substrate metal, for example  
17 using a technique such as physical vapor deposition. However, when  
18 a coating is deposited on the substrate metal by physical vapor  
19 deposition, there are potential adhesion problems between the  
20 substrate metal and the coating. Also, pinholes may form in the  
21 coating, which could lead to accelerated corrosion. A second  
22 method of forming a surface layer is ion beam-assisted deposition  
23 (IBAD). According to this method, a layer is deposited on the  
24 surface of the substrate metal while an ion beam is directed to the  
25 layer at an implantation energy which is significantly less than

1 that used for standard ion implantation. It has been suggested  
2 that IBAD coatings should be greater than 0.5 microns in thickness  
3 in order to cover defects in the modified layer. Thus, coatings  
4 and IBAD have inherent drawbacks when used as a means of preventing  
5 corrosion.  
6

7 **Summary of the Invention**  
8

9 Accordingly, it is an object of the present invention to  
10 provide a method of reducing surface corrosion in metals which does  
11 not involve conventional alloying.

12 Another object of the present invention is to produce a  
13 corrosion-resistant metal which does not involve coating the  
14 substrate metal.

15 It is yet a further object of the present invention to provide  
16 a method of ion implantation in which fewer implanted atoms are  
17 eroded by sputtering.

18 According to the present invention, a metal, such as iron,  
19 steel, aluminum and an aluminum alloy, is placed in an ion  
20 implantation vacuum chamber. Oxygen is then introduced into the  
21 ion implantation vacuum chamber to a pressure in the range of  $1 \times 10^{-5}$   
22 torr to  $10 \times 10^{-5}$  torr. Then, a beam of ions, such as tantalum  
23 ions, are directed at the surface of the substrate metal.

24 The metallic surface layer of the present invention has  
25 implanted metal atoms integrated with substrate metal atoms. The

1 substrate metal has a peak implanted atom concentration of at least  
2 5 atomic % and the implanted layer extends to a depth of over 250  
3 Å.

4  
5 **Brief Description of the Drawings**

6  
7 The accompanying drawings illustrate several aspects of the  
8 present invention, and together with the detailed description,  
9 serve to explain the principles of the present invention. In the  
10 drawings:

11 Figure 1 is a table comparing conventional best vacuum ion  
12 implantation of steel and oxygen backfill ion implantation of  
13 steel;

14 Figure 2 is a graph showing a depth profile of steel implanted  
15 with oxygen backfill;

16 Figure 3 is a graph comparing the corrosion behavior of steel,  
17 best vacuum implanted steel and steel implanted with oxygen  
18 backfill;

19 Figure 4 is a graph showing a depth profile of steel implanted  
20 by conventional techniques;

21 Figure 5 is a graph comparing corrosion behavior of pure  
22 aluminum and aluminum implanted by various techniques; and

23 Figure 6 is a table comparing the corrosion resistance of pure  
24 aluminum with that of aluminum implanted by various techniques.  
25

**Detailed Description of the Preferred Embodiments**

According to the present invention, a method of ion implantation and the metallic surface layer formed therefrom are provided. The method involves implantation using a conventional ion implantation apparatus. In conventional ion implantation, it was thought that the implantation chamber should be maintained as close as possible to a perfect vacuum ("best vacuum"). The reason for a best vacuum is so that the ions being implanted don't collide with other particles and scatter. In conventional ion implantation, the best vacuum condition is approximately  $8 \times 10^{-7}$  torr.

Unlike conventional ion implantation methods, according to the present invention, the implantation chamber is not maintained at best vacuum condition. Instead, oxygen is backfilled into the implantation chamber. With the backfilled oxygen, the pressure in the chamber is within the range of 1 to  $10 \times 10^{-5}$  torr, and more typically in the range of 5 to  $10 \times 10^{-5}$  torr. The oxygen reduces sputtering and improves corrosion resistance. Lower oxygen partial pressures may also be similarly useful. At some point, however, the oxygen partial pressure may be so low that no significant improvement in corrosion resistance will occur. This point has not yet been determined. If the oxygen content is too high, problems are caused related to collision of the ion beam with the oxygen molecules (scattering).

1           The present invention improves corrosion resistance for  
2 various metals, including iron, low alloy steels, aluminum and  
3 aluminum alloys.

4           As the ion being implanted, metal ions, and particularly  
5 transition metal ions such as tantalum, titanium, zirconium,  
6 tungsten and molybdenum, are typically used. Ions of non-metallic  
7 elements that readily react with oxygen, such as silicon, may also  
8 be used. Most often, the implanted ion, if metallic, will be a  
9 valve metal. As the implantation energy, which is related to the  
10 speed imparted to the ions directed at the metal substrate and the  
11 depth of the implanted atoms, conventional implantation energies  
12 can be used. For example, an implantation energy in the range of  
13 25 to 300 keV may be used. If the implantation energy is too low,  
14 the resulting surface layer is too shallow.

15           According to the present invention, a conventional dose of  
16 ions to the substrate metal is used. For example, steel can be  
17 dosed with  $1 \text{ to } 2 \times 10^{17}$  ions/cm<sup>2</sup>. For aluminum, a typical dose may  
18 be in the range of  $4 \text{ to } 8 \times 10^{16}$  ions/cm<sup>2</sup>.

19           A metallic surface layer is produced by the above method. The  
20 metallic surface layer has implanted atoms integrated with  
21 substrate metal atoms. The implanted atoms and the substrate metal  
22 atoms form a solid solution surface alloy at the surface of the  
23 substrate metal; the metallic surface layer has a peak implanted  
24 atom concentration of at least 5 atomic % and the implanted layer  
25 extends to a depth of over 250 Å. Preferably, there is a peak



Docket No.: N.C. 76,497  
Inventor's Name: Sartwell et al.

PATENT APPLICATION

1 implanted atom concentration of at least 5 atomic %, with the  
2 implanted layer extending to a depth of 400 to 500 Å. In contrast,  
3 the implanted atom concentration at the outer surface of the  
4 substrate, may be very low in some cases. For example, when the  
5 substrate is aluminum, the implanted atom concentration in the near  
6 surface region (as determined by x-ray photoelectron spectroscopy)  
7 is on the order of 1 atomic percent. Apparently, this low near  
8 surface concentration increases to a peak concentration above the  
9 5 atomic percent preference further into the bulk aluminum.

10  
11 Having described the invention, the following examples are  
12 given to illustrate specific applications of the invention  
13 including the best mode now known to perform the invention. These  
14 specific examples are not intended to limit the scope of the  
15 invention described in this application.

16  
17 EXAMPLES

18 First Embodiment

19 According to the first embodiment of the present invention,  
20 iron or low alloy steel is implanted with tantalum atoms.

21  
22 **Example 1**

23 Example 1 was prepared by cutting a 0.5" diameter hardened M50  
24 steel rod to a thickness of 1/8". One face of the steel rod was  
25 polished to a diamond finish with 0.25 μm diamond paste in

1 accordance with conventional techniques. Tantalum ions were  
2 implanted at normal incidence into the metal substrate (polished  
3 steel surface) at an implantation energy of 150 keV. A dose of  
4  $1 \times 10^{17}$  ions per  $\text{cm}^2$  was used. Oxygen was introduced into the  
5 chamber with a resulting chamber pressure of  $5 \times 10^{-5}$  torr.

6 Conventional Rutherford backscattering (RBS) was used to  
7 determine how much of the implanted tantalum remained, and thus,  
8 how much tantalum was lost due to sputtering. As shown in Figure  
9 1, the areal density of tantalum in Example 1 was found to be  $0.88$   
10  $\times 10^{17}$  atoms/ $\text{cm}^2$ . Areal density, while expressed in units of  
11 atoms/ $\text{cm}^2$ , is actually a measure of the total number of atoms  
12 present in the surface layer. The areal density of oxygen was  
13 found to be  $3.6 \times 10^{17}$  atoms/ $\text{cm}^2$ . No carbon was present. It should  
14 be noted that, if no tantalum was lost due to sputtering, the areal  
15 density of tantalum would be equal to the dose of tantalum, in this  
16 case,  $1 \times 10^{17}$  atoms/ $\text{cm}^2$ .

17 Through analysis of the surface layer, it was found that an  
18 almost pure tantalum oxide ( $\text{Ta}_2\text{O}_5$ ) layer was formed. Even under the  
19 assumption that the presence of oxygen reduced the sputtering of  
20 tantalum atoms, the formation of a tantalum oxide film is not  
21 predicted, thereby making this an unusual and somewhat remarkable  
22 result.

## 23 24 **Example 2**

25 Example 2 was prepared by implanting M50 steel with tantalum

1 according to the method used for Example 1, except that a dose of  
2  $2 \times 10^{17}$  ions/cm<sup>2</sup> was used. The results of RBS analysis are shown  
3 in Figure 1. As can be seen, doubling the dose from 1 to  $2 \times 10^{17}$   
4 ions/cm<sup>2</sup> increased the areal density of tantalum atoms from 0.88 to  
5  $1.25 \times 10^{17}$  atoms per cm<sup>2</sup>. The areal density of oxygen increased to  
6  $3.8 \times 10^{17}$  atoms per cm<sup>2</sup>.

7 A depth profile was performed on the steel substrate, with the  
8 results being shown in Figure 2. Conventional Auger electron  
9 spectroscopy (AES) was used for the depth profile. According to  
10 the AES method, the surface of the target metal is sputtered away  
11 and the concentration of iron, carbon, tantalum and oxygen is  
12 measured as the sputtering progresses. At the later sputtering  
13 times, a deeper concentration is determined. Thus, the sputtering  
14 time is related to the depth of the implanted layer. As can be  
15 seen from Figure 4, the tantalum concentration did not fall below  
16 20 atomic % until a sputtering time of approximately 650 seconds.  
17 650 seconds would correspond to a depth of approximately 400 Å.

18 Electrochemical corrosion studies were performed on Example 2.  
19 In the studies, the substrate metal was attached to electrode  
20 holders. The edge of the face to be tested and the sides of the  
21 substrate were masked with several coats of an insulating paint.  
22 Electrochemical measurements were made in deaerated 0.1 M NaCl  
23 solution using a conventional corrosion cell. The 0.1 M NaCl  
24 solution was made with reagent grade NaCl and triply distilled  
25 water. The solution pH was 5.8. Ar was used to deaerate the

1 solution. The metal substrate was immersed in the solution for 24  
2 hours to establish a steady state open circuit potential. The  
3 anodic polarization curve was determined using a potential step  
4 technique with the results being shown in Figure 3. The current  
5 density (plotted on logarithmic scale in  $\mu\text{A}/\text{cm}^2$ ) is shown on the Y  
6 axis. The current density is related to how rapidly the metal is  
7 corroding. On the X axis, the potential is recorded as the voltage  
8 of the saturated Calomel electrode ( $V_{\text{SCE}}$ ). As shown by the curve  
9 for Example 2, the current density at a potential of  $-0.4 V_{\text{SCE}}$  is  
10 between 1 and  $0.1 \text{ mA}/\text{cm}^2$ .

11 As in Example 1, analysis of the surface layer of Example 2  
12 showed that an almost pure tantalum oxide layer was formed.  
13

#### 14 Comparative Example 1

15 M50 steel was implanted by the same method used for Example 1,  
16 except that the implantation chamber was maintained at best vacuum  
17 conditions. That is, the pressure in the chamber was approximately  
18  $8 \times 10^{-7}$  torr and substantially no oxygen was present. As can be  
19 seen in Figure 1, the areal density of tantalum was shown to be  
20  $0.43 \text{ atoms}/\text{cm}^2$ . As expected, no oxygen was present. The areal  
21 density of carbon was  $0.2 \text{ atoms}/\text{cm}^2$ .  
22

#### 23 Comparative Example 2

24 M50 steel was implanted according to the same procedure used  
25 for Comparative Example 1, except that a dose of  $2 \times 10^{17} \text{ ions}/\text{cm}^2$

1 was used. As shown in Figure 1, doubling the dose only increased  
2 the tantalum concentration from 0.43 to  $0.46 \times 10^{17}$  atoms/cm<sup>2</sup>.  
3 However, introducing oxygen into the chamber did significantly  
4 increase the amount of tantalum retained in the metal substrate by  
5 almost a factor of 3 for incident doses of  $2 \times 10^{17}$  ions/cm<sup>2</sup>  
6 (compare Example 2 and Comparative Example 2).

7 A depth profile was performed on Comparative Example 2 using  
8 AES and the same procedure used for Example 2. As shown in Figure  
9 4, the tantalum concentration fell below 20 atomic % at a  
10 sputtering time of approximately 450 seconds. 450 seconds would  
11 correspond to a depth of only approximately 250 Å, a depth of 150  
12 Å less than that for Example 2.

13 Electrochemical corrosion studies were performed on  
14 Comparative Example 2 using the same techniques as used for Example  
15 2. The results are shown in Figure 3. As can be seen from the  
16 curve of Comparative Example 2 shown in Figure 3, the corrosion  
17 resistance is less (more rapid corrosion) when oxygen is not used  
18 in the ion implantation chamber. For a potential of  $-0.4 V_{SCE}$ , the  
19 current density was between 1 and 10 mA/cm<sup>2</sup>.

20 The pitting resistance was determined for Example 2 and  
21 Comparative Example 2 based on the results shown in Figure 3. A  
22 higher (more positive) pitting resistance represents an increased  
23 resistance to pit initiation. That is, the pitting resistance is  
24 the  $V_{SCE}$  where the current density begins to rapidly increase. At  
25 his point, the corrosion resistance begins to fall. The pitting

1 resistances for Example 2 and Comparative Example 2 were -0.450 and  
2 -0.400  $V_{SCE}$ , respectively.

3 The density of the pits on Example 2 and Comparative Example  
4 2 was measured by conventional techniques, and the density was much  
5 higher for Comparative Example 2 in which there was no oxygen  
6 backfill. The results of these tests indicate that the tantalum  
7 implanted with oxygen backfill (Example 2) produced corrosion  
8 resistance better than tantalum implantation by itself.

9  
10 **Comparative Example 3**

11 In Comparative Example 3, a M50 steel rod was tested. No ion  
12 implantation was used for Comparative Example 3. Electrochemical  
13 corrosion studies were performed on Comparative Example 3 using the  
14 same techniques as used on Example 2 and Comparative Example 2.  
15 The results are shown in Figure 3. As can be seen from the curve  
16 for Comparative Example 3, the corrosion resistance for an  
17 unimplanted M50 steel rod is orders of magnitude worse than that  
18 for the implanted rods of Example 2 and Comparative Example 2. For  
19 a potential of -0.4  $V_{SCE}$ , the current density was between 100 and  
20 1000 mA/cm<sup>2</sup>.

21 As shown in Figure 3, at a potential below -0.25  $V_{SCE}$ , the  
22 current density was at least two orders of magnitude higher than  
23 that for Example 2 (oxygen backfill) and Comparative Example 2  
24 (best vacuum). Scanning electronmicrographs, in conjunction with  
25 the polarization curves of Figure 3, showed that the M50 steel

underwent extensive uniform corrosion, whereas both of the implanted samples (Example 2 and Comparative Example 2) did not.

**Embodiment 2**

According to a second embodiment of the present invention, it is possible to implant ions into aluminum or aluminum alloys.

**Example 3**

A 99.999% pure aluminum sample was polished to a 1  $\mu\text{m}$  finish using conventional techniques. Tantalum ions were implanted at normal incidence into the aluminum metal substrate at an energy of 150 keV at a dose of  $4 \times 10^{16}$  ions/cm<sup>2</sup>. Oxygen was introduced into the implantation chamber to a pressure of  $5 \times 10^{-5}$  torr. The implantation was carried out at room temperature (RT).

**Example 4**

Example 4 was prepared in the same manner as that used for Example 3 except that a dose of  $8 \times 10^{16}$  ions per cm<sup>2</sup> was used.

**Comparative Example 4**

Comparative Example 4 was prepared in the same manner as that used for Example 3 except that the implantation chamber was maintained at best vacuum conditions (BV). That is, the pressure in the implantation chamber was approximately  $8 \times 10^{-7}$  torr. Further, an implantation energy of 100 keV, rather than 150 keV,

1 was used.

2  
3 **Comparative Example 5**

4 Comparative Example 5 was prepared in the same manner as  
5 Comparative Example 4 except that the implantation was conducted at  
6 the temperature of liquid nitrogen (LN<sub>2</sub>) rather than at room  
7 temperature. The implantation was performed at liquid nitrogen  
8 temperature to inhibit radiation and enhance diffusion of the  
9 tantalum away from the surface. Further, an implantation energy of  
10 100 keV, rather than 150 keV, was used.

11 **Comparative Example 6**

12 Comparative Example 6 was prepared in the same manner as  
13 Example 4 except that aluminum ions were implanted instead of  
14 tantalum ions. Aluminum was implanted into the aluminum for the  
15 purpose of determining if the improved corrosion resistance was  
16 simply the result of the presence of oxygen in the chamber, or the  
17 result of the interaction of the implanted tantalum with oxygen,  
18 similar to what was observed for the first embodiment.

19  
20 **Comparative Example 7**

21 Comparative Example 7 was prepared in the same manner as  
22 Example 4 except that the pressure in the implantation chamber was  
23 maintained at best vacuum, approximately  $8 \times 10^{-7}$  torr.

24  
25 **Comparative Example 8**



1           In Comparative Example 8, a 99.999% pure polished aluminum  
2           (the metal substrate) was used. The metal substrate was not dosed  
3           with implantation ions.

4           Electrochemical corrosion studies were performed on Example 3  
5           and Comparative Examples 3-5 and 8 in the same manner as that done  
6           for the first embodiment. The results of the electrochemical  
7           corrosion studies are shown in Figure 5. As can be seen in Figure  
8           5, the anodic polarization curves are plotted for Example 3 (RT,  
9           Ox), Comparative Example 4 (RT, BV), Comparative Example 5 (LN<sub>2</sub>,  
10          BV) and Comparative Example 8 (Al). As shown in Figure 5, Example  
11          3 exhibited the greatest increase in pitting potential, followed in  
12          order by Comparative Example 5, Comparative Example 4 and  
13          Comparative Example 8. Higher pitting potentials indicate a  
14          greater resistance to pit initiation.

15          Figure 6 shows a summary of results for tests performed on  
16          Examples 3 and 4, and Comparative Examples 4-8. In the fifth  
17          column is the pitting potential ( $E_{pit}$ ) as determined from anodic  
18          polarization curves, some of which are shown in Figure 5. For  
19          example, as to Comparative Example 8, the slope of the respective  
20          anodic polarization curve increases greatly at a pitting potential  
21          of  $-0.700 V_{SCE}$ . At this point, the aluminum is beginning to rapidly  
22          undergo pitting corrosion. In the sixth column of Figure 6, the  
23          pitting potential of Examples 3 and 4, and Comparative Examples 4-7  
24          is compared with that of Comparative Example 8 (the unimplanted  
25          aluminum sample).

1           In the seventh column of Figure 6, the oxide thickness is  
2           given in Å. The oxide thickness was determined by conventional X-  
3           ray photoelectron spectroscopy. Although the X-ray photoelectron  
4           spectroscopy method has a margin of error, it can be seen that the  
5           oxide thickness did not vary substantially. X-ray photoelectron  
6           spectroscopy has also shown that the near surface concentration is  
7           significantly lower than in the case of the M-50 steels. Moreover,  
8           the aluminum samples made using reactive oxygen-assisted ion  
9           implantation according to the present invention appear to have a  
10          lower near surface concentration of tantalum than aluminum samples  
11          implanted with tantalum using best vacuum conditions. These  
12          results contrast with the results obtained by implantation of  
13          tantalum into M-50 steel.

14          As shown in Figure 6, for those samples implanted with a dose  
15          of  $4 \times 10^{16}$  ions/cm<sup>2</sup>, tantalum implantation alone (Comparative  
16          Example 4) produced only a very small increase (improvement) in  
17          pitting potential. Implantation of tantalum at liquid nitrogen  
18          temperature with no oxygen (Comparative Example 5) resulted in some  
19          additional improvement. However, implantation with oxygen backfill  
20          (Example 3) resulted in a substantial increase in the pitting  
21          potential. For the implantation with a dose of  $8 \times 10^{16}$  ions/cm<sup>2</sup>,  
22          the tantalum implantation at room temperature without oxygen  
23          (Comparative Example 7) again showed a modest increase in pitting  
24          potential (.150 volts). Aluminum implantation at room temperature  
25          with oxygen backfill (Comparative Example 6) resulted in a modest

1 increase as well. However, a very substantial increase in the  
2 pitting potential was obtained for the sample implanted with  
3 tantalum at room temperature with oxygen present (Example 4).  
4 Example 4 had an average pitting potential of .750 volts higher  
5 than that of pure aluminum, and .600 volts higher than that of  
6 tantalum implanted without oxygen at the same dose (Comparative  
7 Example 7), despite their apparently lower near surface  
8 concentration of tantalum.

9 The present invention provides many benefits over conventional  
10 ion implantation. In steel, an almost pure tantalum oxide layer  
11 was formed, thereby improving corrosion resistance. In aluminum,  
12 the modified surface layer was extremely resistant to pit  
13 initiation.

14 The metal substrate having a modified surface layer produced  
15 in accordance with the present invention could be very useful in  
16 the electronics industry, where small pits in aluminum can lead to  
17 failure of a device. Further, it could be useful in the aeronautic  
18 industry, to impart corrosion resistance to bearings, gears and  
19 other components fabricated from low alloy steels or aluminum  
20 alloys which are highly susceptible to pitting corrosion.

21 Numerous modifications and variations of the present invention  
22 are possible in light of the above teachings. It is therefore to  
23 be understood that , the  
24 invention may be practiced otherwise than as specifically described  
25 herein.

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PATENT APPLICATION

#### ABSTRACT

A method of ion implantation using oxygen backfill and a modified surface layer formed therefrom are provided. The method of ion implantation includes the steps of placing a substrate metal in an ion implantation vacuum chamber, introducing oxygen into the ion implantation vacuum chamber and directing a beam of ions at the substrate metal. The modified surface includes a substrate metal and implanted atoms at a surface of the substrate metal. The implanted atoms are integrated with the substrate metal. The substrate metal has an implanted atom concentration of at least 5 atomic % to a depth of over 250 Å.